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A Wearable Skin-Stretching Tactile Interface for Human-Robot and Human-Human Communication

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Abstract—Currently, the majority of wearable robotic haptic feedback devices rely on vibrations for relaying sensory information to the user. While this can be very effective, vibration as a physical stimulation is limited in modality and is uncommon in the natural world. In many cases, for human-robot and human-human interaction, a more natural, affective tactile interaction is needed to provide comfortable and varied stimuli. In this work we present the Super-Cutaneous Wearable Electrical Empathic Stimulator (SCWEES), a tactile device that gently stretches and squeezes the surface of the skin. Our hypothesis is that this device can create a pleasant, unobtrusive sensation that can be used to mediate social interactions or to deliver subtle alerts. We describe the design of the SCWEES, a lightweight 3D-printed semi-flexible structure that attaches to the skin at two points and actuates via two shape-memory alloy coil actuators. We evaluate the SCWEES through a range of human interaction experiments: stimulation strength and pleasantness, contraction and extension, and the conveyance of non-disruptive notifications. Quantitative and qualitative results show that the SCWEES generates a pleasant sensation, can convey useful information in human-machine interactions, and delivers affective stimulation that is less disruptive than conventional vibratory tactile stimulation when the user is engaged in a task.

Index Terms—Wearable Robots; Haptics and Haptic Interfaces; Social Human-Robot Interaction; Soft Robot Applications; Affective Tactile Stimulation

I. INTRODUCTION

TOUCH is a predominant sense, not only for perceiving our environment, but also for social interactions. Our skin is a multimodal sensor capable of detecting touch, stretch, temperature, texture, vibration, pressure and pain [1], [2]. Haptic feedback as a form of sensory feedback has long been an area of interest and is still being explored. Applications include force feedback in virtual reality surgery [3], improving prosthesis-body interfaces in the medical field [4], and enhancing military training, augmented reality and immersive experiences in gaming [5]. A major challenge in

current wearable tactile devices is the trade-off between the cost, comfort, and portability of the device, and its provision of a realistic feeling of touch [6].

Haptic wearable devices come in a wide range of shapes, sizes and interaction modalities, including insoles that aid navigation for the visually impaired [7], kinesthetic haptic feedback to guide a user's hand [8] and active pin arrays for laterotactile stimulation [9]. The majority are vibrotactile, where sensory information is relayed to the body by the use of vibrations with differing frequency, amplitude, duration, and/or waveform [2], [10], [11].

Although an effective tactile interface modality, vibrations produced by motors are not a natural sensation, nor are they very localised. Despite efforts to ‘anthropomorphise’ vibrotactile stimulation [12], these characteristics make them unfavourable for inter-person communication, where a more natural sensation of touch is needed. The importance of haptic feedback for inter-person communication has long been known [13], [14] and there is evidence to suggest that mediated social touch is processed in a similar way to real physical contact [15]. Applications include augmenting long-distance phone calls by enabling users to send and receive a “hug”, aiding rehabilitation where the patient can feel the physiotherapist demonstrating the desired movement, and delivering non-interruptive notifications. Devices which deliver more natural, affective touch could also improve engagement in human-robot interaction.

Over the past decade, a number of devices have utilised skin stretching methods as alternatives to vibratory stimulation, delivering navigation feedback [16], guided movement [17], [18] and robotic manipulator control [19], [20]. Different methods have been devised to stretch the skin, often using

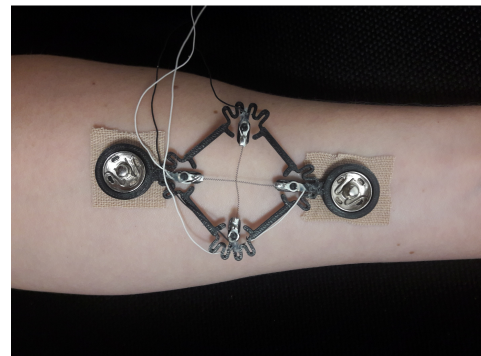


Fig. 1: The SCWEES attached to the user's inner forearm, using two adhesive pads on the skin, affixed to the device by popper studs.

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servomotors controlling end-effectors that either move, rotate or rock [21], [16], [20].

Skin stretch has been shown to be superior to vibratory feedback to convey proprioception information [22] and all of these devices demonstrate the effectiveness of non-vibrational tactile sensations as an information channel. While they show considerable potential, the majority are powered by servomotors which are often bulky and noisy. In addition, the analyses of these devices do not explore the affective response of users to the device, such as the pleasantness of the sensations.

In this article, we explore the use of Shape-Memory Alloys (SMAs) to generate a more delicate and subtle haptic feedback mechanism. SMAs are lightweight, flexible and actuate silently, beneficial properties for use in an unobtrusive wearable device as exploited in tactile pin-arrays [23], [24], [25] and fingertip-mounted skin stretching devices [26]. Here, we use SMAs to generate lateral skin stretching by means of a lightweight, wearable device attached to the skin on the inner forearm. The forearm was chosen as an easily accessible region of the body which presents a large area of sensitive skin. The device provides gentle stretching and squeezing of the skin (Figure 1) with the goal of instigating a more localised and natural feeling. We present the Super-Cutaneous Wearable Electrical Empathic Stimulator (SCWEES) and investigate three important characteristics:

1. The stretching/squeezing sensation in terms of affective response measured by pleasantness and strength,
2. The use of this device for inter-person interactions,
3. The use of this device for non-disruptive alerts when carrying out everyday tasks.

II. SYSTEM DESIGN

In this section we describe the SCWEES device. We define three core requirements for the design:

Low visual and auditory disturbance to the user. Many existing tactile devices use vibrational motors or servomotors which can be bulky and produce noticeable levels of sound. For this experiment we chose to use SMAs to generate movement as they are silent, lightweight and unobtrusive.

Simple and quantifiable tactile sensations. To reduce the ambiguity of sensations and obtain clear base-line psychometric results we designed the device with two specific and repeatable modes of stimulation; extension and contraction with predetermined displacements.

Minimally intrusive for the user. The device was designed for use on the inner forearm, an area easily accessible and commonly used for social touch. We also made the device as lightweight and unobtrusive as possible at this prototype stage by 3D printing a small frame for attachment to the skin while keeping the driver electronics separate and out of view of the user.

A. Hardware and Fabrication

The SCWEES device is a 3D-printed (polylactic acid plastic) planar diamond-shaped structure (Figure 1) with flexible elements at the four corners that act as hinges. Two SMA coils (Toki Biometals) are mounted orthogonally between opposite corners. As a safety measure, the SMA coils are suspended

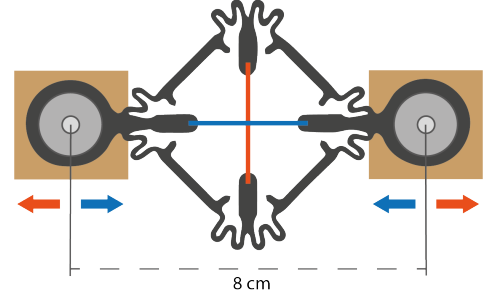


Fig. 2: The SCWEES tactile stimulation device. On activation of the horizontal SMA (blue), the ends of the device are pulled closer together, compressing the skin. On activation of the vertical SMA (orange), the ends of the device extend, stretching the skin. Deformation limiters (C) constrain maximum displacement in both directions.

on raised pins 4 mm above the skin, minimising any risk of harm to the user or interference of the tactile sensation that could occur from the heat of the activated SMA wire (transition temperature 70 °C). The diamond structure couples the two actuators such that contraction of one SMA extends the counter SMA as shown in Figure 2. At each corner, deformation limiters cap the maximum stroke of the device to ± 5 mm, ensuring repeatability of stimuli. Two circular rings are connected at opposite corners into which female poppers are inserted. These connect to the adhesive pads on the skin via male popper fastenings allowing for easy application, modification and removal. The device was connected to a control system via four very thin and flexible insulated multi-core wires. Each SMA was driven by up to 5 V using a power transistor controlled by an Arduino Nano. Voltage control was achieved using Pulse Width Modulation (PWM) from 0 to 100% duty cycle. The Arduino interfaced to a PC for high level control and data processing. The total weight of the device on the arm was 2.5 g and its height was 5 mm making it comfortable and unobtrusive to wear.

For comparison to existing vibrotactile devices such as smart watches, a low mass vibration motor was also used in experiments, attached with the same size adhesive pad next to the SCWEES device. The 3.3 V, 1 A motor had 3 mm thickness, 10 mm diameter, weighed 1 g and exhibited negligible spin-up time compared to the SCWEES device.

B. Device Characterisation

To characterise the device, the displacement was recorded while triggering the contracting SMA (blue in Figure 2) with a 1 V step function for 5 s. Voltage and current were recorded via a galvanostat connected to a National Instruments data acquisition device (NI-USB 6009). Results in Figure 3 show a delay of approximately 1 s as the SMA heated up and a maximum displacement of 2.3 mm at this voltage. The device was characterised while not attached to a human, free to move on a smooth surface, ensuring a controlled test environment. For comparison, the displacement of the device when mounted on the arm and actuated at 1 V is also shown.

The frequency response of the device was characterised

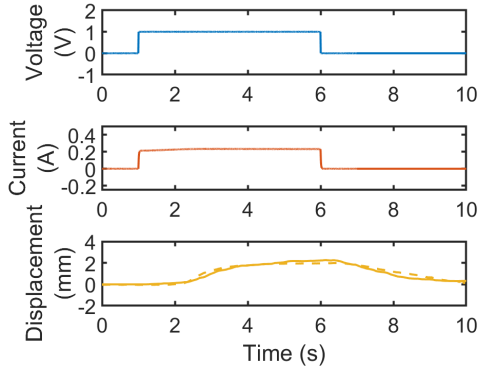


Fig. 3: Device characterisation using a 1 V step input to the contracting SMA with the device free to move on a flat surface (solid), and displacement when worn on the forearm (dashed).

by recording displacement while activating the contracting SMA with a 1 V square wave of increasing frequency. Five oscillations were recorded at frequencies ranging from 0.1 Hz to 10 Hz. The Bode plot is shown in Figure 4, from which the interpolated bandwidth (at the -3 dB level) was found to be 0.216 Hz.

Figure 5 shows variation of blocking (maximum) force of the SCWEES device with displacement. In an idealised system, extensive force would reduce from maximum when the device is fully contracted to zero when the device is fully extended, while contractile (negative) force would increase from zero when the device is fully contracted to a maximum when the device is fully extended. Differences in behaviour between the SCWEES device and the idealised system are attributed to buckling of the structure as a result of the slightly offset SMAs.

Contractile force generally matches the idealised system, except for exerting a small positive force when the device is fully contracted: in this case, contraction of the SMA results in the device buckling out of plane, extending slightly and inducing a small positive force on the load cell.

Extensive force differs more from the idealised system. The extensive SMA does not exert force directly in the same way as the contractile SMA, rather exerting it by deforming the SCWEES device structure. Buckling of the structure allows it to exert force by bending out of plane, even when fully extended.

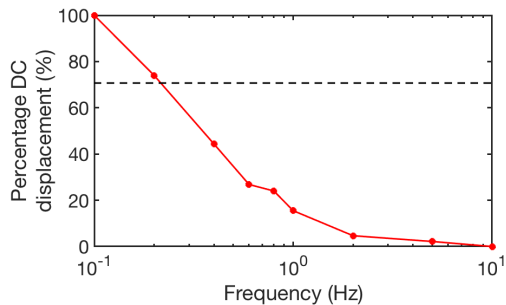


Fig. 4: Bode plot for SCWEES device using a 1 V square wave input to the contracting SMA. 100% DC displacement corresponding to 2.3mm displacement shown in Figure 3.

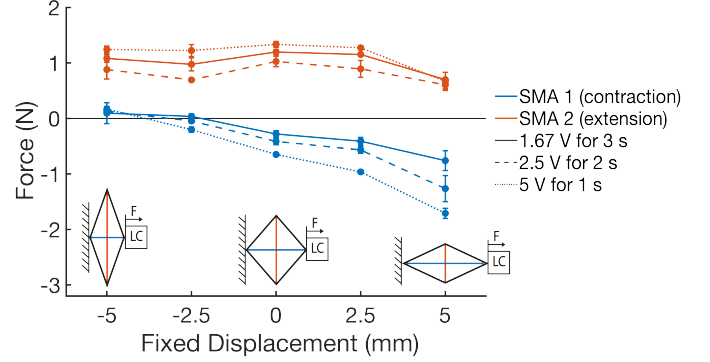


Fig. 5: Peak blocking force for SCWEES device, SMAs individually activated at three voltage levels. Displacement measured from neutral position (-5mm: fully contracted, 5mm: fully extended). Points are averages of three trials and error bars show standard deviation across trials.

III. EXPERIMENT DESIGN

To evaluate the effectiveness of the SCWEES device we undertook a series of psychophysical experiments. Ten volunteers (8 males, 2 females, with an age range of 20 to 40 years old) participated in the study. The device was attached to the inner forearm of the participant's non-dominant arm during the experiment. The duration of the experiment was approximately 30 minutes, comprising of three separate sections outlined below.

A. Experiment Setup

Figure 6 shows the experiment setup used for participants. All three sections of the experiment were controlled through the Arduino Nano via serial communication with MATLAB on a laptop PC. The stimuli were randomly permuted and the order was recorded for each participant.

All electronics were encased to minimise distraction to the participants, and a square tube was fabricated to cover the forearm from view during the experiment, eliminating visual feedback from the device. All other distractions were kept to a minimum by undertaking the experiment in a quiet room with no other people or external disturbances.

B. Section 1: Sensation

In this section, we investigated the affective response of users to the SWEES device. Participants were subjected to six different stimuli; three modes of contraction and three modes of extension. These three modes were defined by their duration of 1, 2, or 3 seconds and voltage of 5, 2.5 and 1.67 V, chosen so that the maximum displacement of the device was consistently reached in each case. We used data from Figure 3 to estimate the power delivered to a single SMA: the minimum resistance of the SMA coil was 4.34Ω , implying input powers of 5.77 W, 1.44 W and 0.64 W respectively.

The affective response of participants was recorded by asking them to rate the pleasantness and strength of each sensation experienced. These subjective parameters are defined in the circumplex model of affect [27] commonly used in psychology for measuring affective response. The circumplex model is a means of simplifying the wide range of affective

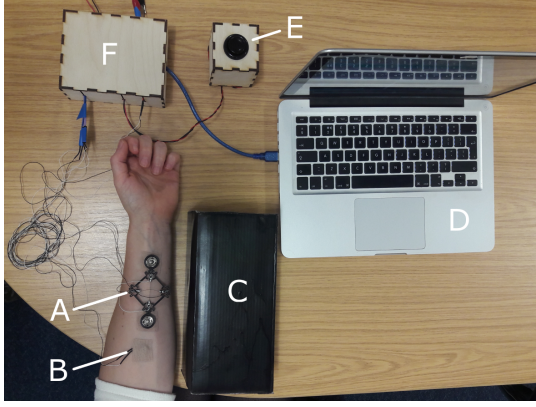


Fig. 6: Experiment setup; A) SCWEES device and B) vibration motor attached to forearm. C) Square tube into which participants place their forearm throughout the experiment. D) Laptop computer as controller. E) Push button for participants to press when detecting stimuli. F) Control box containing Arduino Nano and transistor drivers.

responses into two parameters; valence (pleasantness) and intensity (strength). Both were rated on a 10 point scale, pleasantness from -5 to 5 (very unpleasant to very pleasant, 0 equating to neutral), and strength from 0 to 10 (no sensation to very strong sensation). Each stimulus was repeated 5 times so a total of 30 stimuli were presented in a random order to each participant.

C. Section 2: Mimicking Movement

The ability of participants to detect the type of sensation given by the device and physically respond to it was investigated. One application of this tactile stimulation is in body-to-body communication. The movement of one person, such as flexing their wrist, can be relayed to a second person via the SCWEES device as a form of tactile communication. For the experiment the participants were told to flex their wrist when they felt a contraction on the skin and to extend their wrist when they felt an extension. Ten repetitions of each stimulus - contraction and extension - were given in randomised order and the response of participants was recorded by the experimenter. The SMAs were activated using a 1 s, 5 V step input.

D. Section 3: Distraction

In this section, we investigated the capability of participants to detect sensations from the SCWEES device when performing other tasks. This enabled a comparison of the device with current vibrotactile alerts such as the vibration of a smart watch indicating an incoming message. The vibration motor was run at 3.3 V for 200 milliseconds (selected to mimic the vibration notification of a low-cost ID130Plus smart watch). The SCWEES device was actuated at 3.3 V for 600 milliseconds to provide sufficient time for each SMA to heat and contract. Participants were asked to press a button whenever they felt a sensation from either the vibration motor or the SCWEES device while performing three different tasks: 1. No task - sitting stationary; 2. Reading a book (Harry Potter and the Half-Blood Prince; J. K. Rowling); 3. Playing

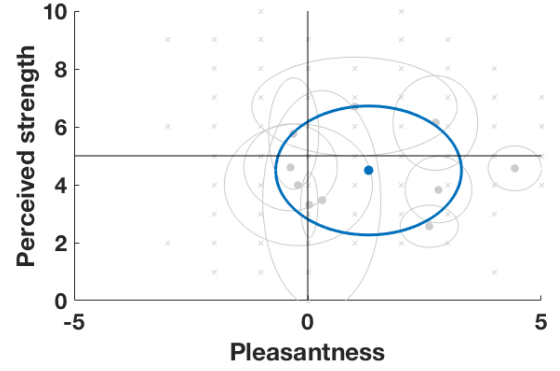


Fig. 7: Mean and standard deviation of responses to all stimuli for all participants in the circumplex plane (blue). Raw data (x's) and individual participant means and standard deviations (solid) shown in grey.

a continuous arcade-style game (Run 3; Autosaur Games).

Each task lasted 5 minutes, during which 20 repetitions of contraction and 10 repetitions of the vibration stimuli were presented to participants at randomised times. If the button was not pressed it was assumed that the participant had not noticed the stimulus. A buffer of 6 seconds was included for each stimulus to ensure that they were presented separately and the participant had time to press the button before the next stimulus.

IV. EXPERIMENTAL RESULTS

A. Section 1: Sensation

Figure 7 shows participant responses in the circumplex plane with mean pleasantness of 1.30 (σ 1.70) and mean strength of 4.49 (σ 1.34). Conducting a one-sided t-test across all pleasantness responses at 1% significance level accepted the alternative hypothesis H_1 of mean pleasantness > 0 . This indicates that the device was generally found to be pleasant. For individual participants, one-sided t-test results at 1% significance level indicate that 5 participants found the device pleasant (H_1 : mean > 0), 4 participants were neutral (H_0 accepted) and 1 participant found it unpleasant (H_2 : mean < 0 , mean pleasantness rating in this case was -0.3). No participants recorded a pleasantness response less than -3.

Across all participants, the duration of the stimuli made a negligible difference to the perceived pleasantness of the sensation (linear correlation coefficient of -0.036 with p-value of 0.54 at the 5% significance level) as demonstrated in Figure 8. However, the perceived strength of sensation had a negative correlation with the stimulus duration (linear correlation coefficient of -0.20 with p-value of 0.00045 at the 5% significance level), indicating that the shorter, faster stimuli felt stronger to participants.

B. Section 2: Mimicking Movement

For the hand flexion test, the mean percentage correct across all participants was 90% (σ 13.3%), split between 89% (σ 14.5%) for contraction (wrist flexion) and 91% (σ 19.1%) for extension (wrist extension). At least half of the participants had a success rate greater than 95% demonstrating that the device was very successful at communicating two separate

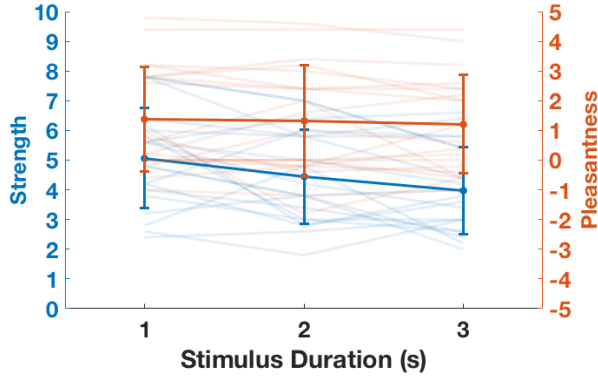


Fig. 8: Mean and standard deviation of perceived strength and pleasantness results across participants for the three durations of stimuli in Section 1.

stimuli to the user. A Welch’s t-test on the contraction and extension success rates accepts the null hypothesis of equal mean with 1% significance level, suggesting no difference between success at detecting flexion and extension.

C. Section 3: Distraction

Figure 9 shows the success rate across participants in Section 3. The mean success rate for the vibration stimuli was 99% during tasks 1 and 2 and 100% during task 3, demonstrating that the vibration stimuli were consistently noticed by participants. This is as expected, given that the vibration alerts on smart watches or phones are designed to be noticed even when the user’s focus is elsewhere.

For the SCWEES device stimuli, when participants had no task or were reading a book they noticed the device with a 96.5% average success rate. When distracted by the game there was a decrease in SCWEES recognition to 89% and many participants commented that the sensation was particularly difficult to notice during this section (see responses in Table I). Conducting Welch’s t-test at the 1% significance level suggests that the noticeability of the SCWEES device was equal to the vibration for no task (A) and reading (B) but not while playing the game (C), for which SCWEES was less disruptive to the user. Conducting a Welch’s t-test between the SCWEES results for playing a game versus no game (C vs A or B) also rejected the null hypothesis. This indicates a significant decrease in noticeability of the device while participants were playing the game.

D. Comments

After the three sections of the experiment were completed, participants were asked to write down any comments or thoughts they had about the experience of wearing the SCWEES device and the sensations it created. Table I shows user comments, providing further evidence of the overall positive reaction of participants to the device. It was generally stated that the sensations felt natural and pleasant, particularly in comparison to the vibrotactile sensations. A common comment was that the sensation felt like a person touching or squeezing their arm which would make it beneficial for use in mediated social touch scenarios. A number of participants mentioned that the device was more difficult to notice when

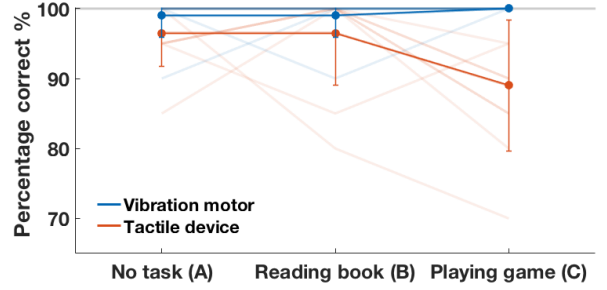


Fig. 9: Mean percentage of correct button presses across all participants for vibration and SCWEES device stimuli during each task; A) no task, B) reading the book and C) playing the game.

playing the game and that if they had not been asked to detect the sensations they would easily have ignored it.

V. DISCUSSION AND CONCLUSION

The SCWEES device was successful in generating natural and pleasant tactile sensations, supported by the results from Section 1 for which the mean pleasantness rating was positive, verified by a one-sided t-test.

The perceived strength of sensations had a negative correlation of -0.20 to the duration of stimuli, as shown in Figure 8, indicating that slower and lower voltage excitations were interpreted as weaker than faster and higher voltage stimuli. Being able to control perceived intensity by changing stimulus duration allows for communication of not only direction (contraction or extension) but also magnitude. Pleasantness was not correlated to stimulus duration overall, rather the affective response was particular to the individual. For example, one participant said that the slower stimuli felt like something crawling on their skin and so were less pleasant, whereas the faster stimuli felt like a person touching or squeezing their arm which they perceived as pleasant.

The SCWEES device can impose either skin compression (contraction) or skin stretching (extension). Overall, the mean discrimination rate across both modalities was 90%, matching previous devices [16], and the difference in how well participants could detect the two stimuli was negligible. This shows the capability of the device to convey information or guide the user’s movement via tactile stimulation. Further investigation is required to fully map the affective response landscape and explore increased modalities.

One hypothesis for the SCWEES device was that it could enable non-intrusive notifications. This was verified in Section 3; participants were able to easily detect sensations when sitting stationary or reading a book, but found these more difficult to detect while playing an arcade-style game (Figure 9).

This indicates that the SCWEES device is less intrusive than vibrotactile stimulation when the user is distracted, an important feature that could enable its use during high-risk activities such as performing surgery or driving a car. In these cases the wearer should not be distracted and these subtle notifications could reduce risk (studies have shown that even handsfree mobile phone use markedly increased mental

Participants' Comments

"The device feels like real fingers squeezing on your arm", "It doesn't feel unpleasant compared with the vibration motor", "Very easy to forget about", "Not as intrusive as other devices", "If I move or shake my hand I will miss the sensation from the device", "Playing a game, I can still [feel the device] but with a slower response", "Simple system that is easy to detect", "So cool!", "The vibration is much easier to notice than the other sensations [from the device]", "It was really nice", "I found it hard to distinguish between the stretching and contracting", "Feels good! Like kind of massage", "I like the feeling of contraction more than that of elongation", "The contraction is not that obvious to tell when reading or playing", "I couldn't really tell the difference between the sensations very well", "I don't think it felt nice or not nice - very neutral. I think expanding was slightly nicer though", "Great", "Very clear sensations, though hard to tell when playing the game", "Very nice experience", "The vibration motor was stronger than the skin stretcher, I really liked that it was continuous in contrast to the binary vibration motor", "Clear sensations", "Mild sensations were unpleasant, larger ones were better", "Extending was easier to detect and felt pleasant", "Did not like the vibrations".

TABLE I: Comments stated by participants at the end of the experiment (duplicates removed).

workload when driving [28]).

There was almost universal agreement that the SCWEES device generated pleasant touch and all participants favoured it over vibrotactile stimulation. This is especially noteworthy given the ubiquity of vibration-based stimuli in today's electronic devices. Tactile devices such as SCWEES have the potential to replace vibrotactile stimulation and enable a new type of affective communication channel for mediated social touch and human-robot interactions. This could be delivered via unobtrusive wearable devices worn on the body or embedded into clothing or objects we interact with.

In the future, we plan to improve the SCWEES device by adding more degrees of freedom and minimising the size of the power supply and control unit so that they can be worn unobtrusively and wirelessly on the body.

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